Science with The Square Kilometre Array

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&
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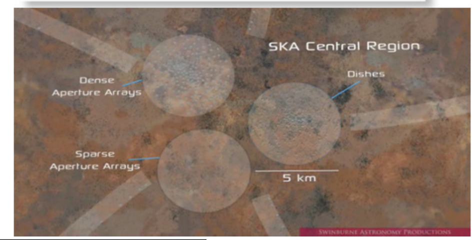
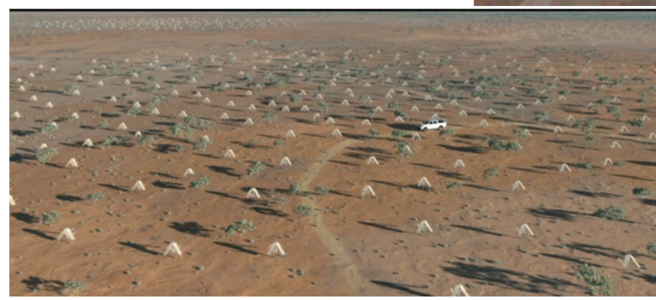
Square Kilometre Array

The Global Radio Wavelength Observatory



- Originally: “Hydrogen telescope”

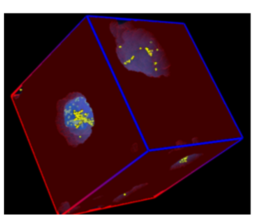
  Detect H I 21-cm emission from Milky Way-like galaxy at $z \sim 1$

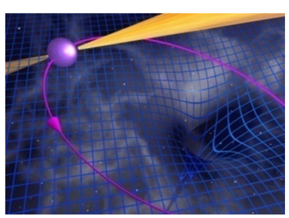


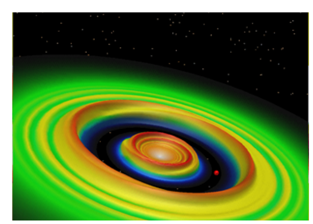
- SKA science much broader

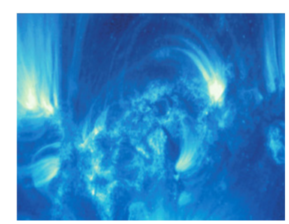
  ⇒ Multi-wavelength, multi-messenger

- On-going technical development
  - Cyber-infrastructure and “big data”
- International involvement







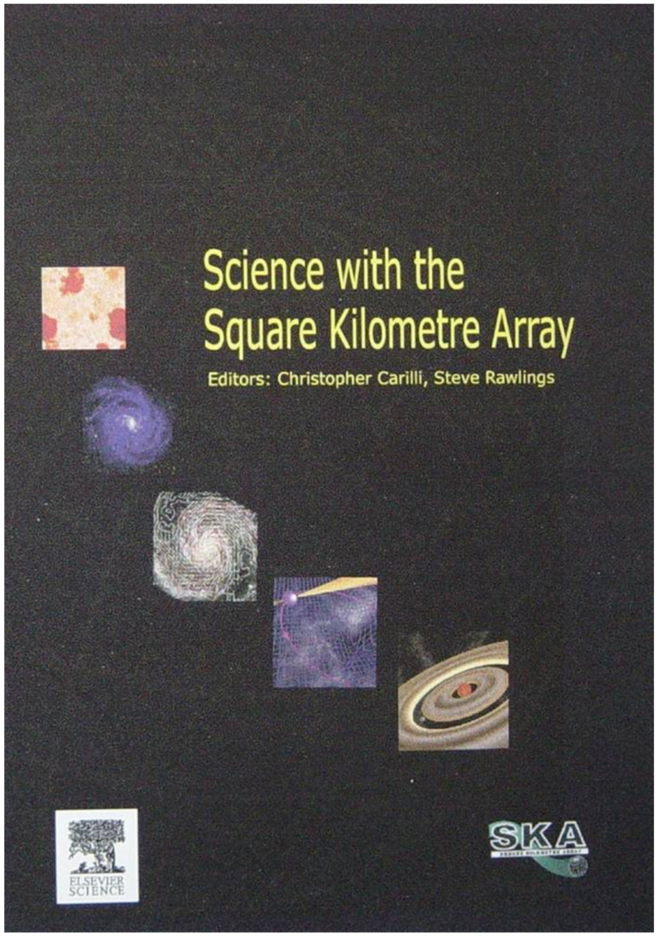


SKA Key Science

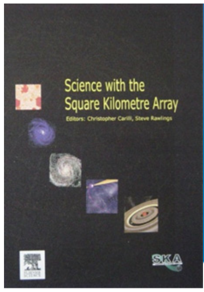
International working group

- Strong-field Tests of Gravity with Pulsars and Black Holes
- Galaxy Evolution, Cosmology, & Dark Energy
- Emerging from the Dark Ages and the Epoch of Reionization
- The Cradle of Life & Astrobiology
- The Origin and Evolution of Cosmic Magnetism

With design philosophy of *Exploration of the Unknown*



Science with the Square Kilometre Array (2004, eds. Carilli & Rawlings, *New Astron. Rev.*, **48**)



21^{st} Century Astrophysics

20^{th} Century: We discovered our place in the Universe.

21^{st} Century: We understand the Universe we inhabit.

Cosmology & Fundamental Physics

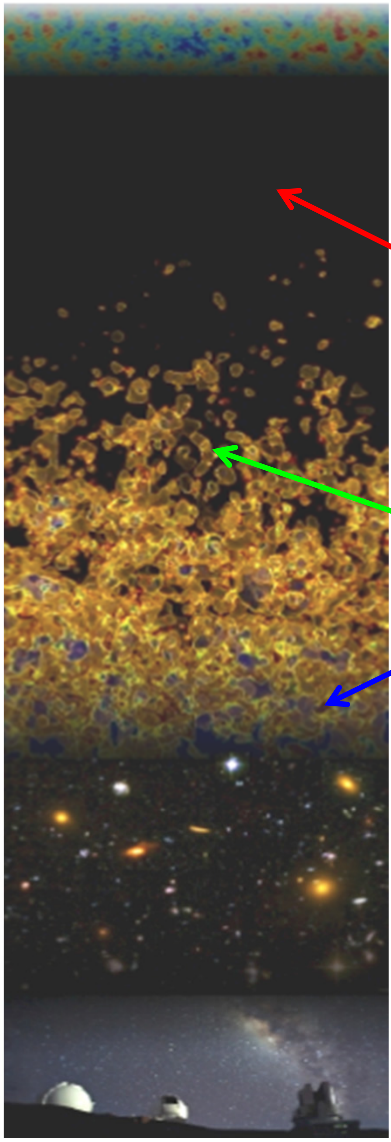
- Gravity
  - Can we observe strong gravity in action?
  - What is dark matter and dark energy? (dark energy and BAOs with H I galaxies)
- Magnetism
- Strong force

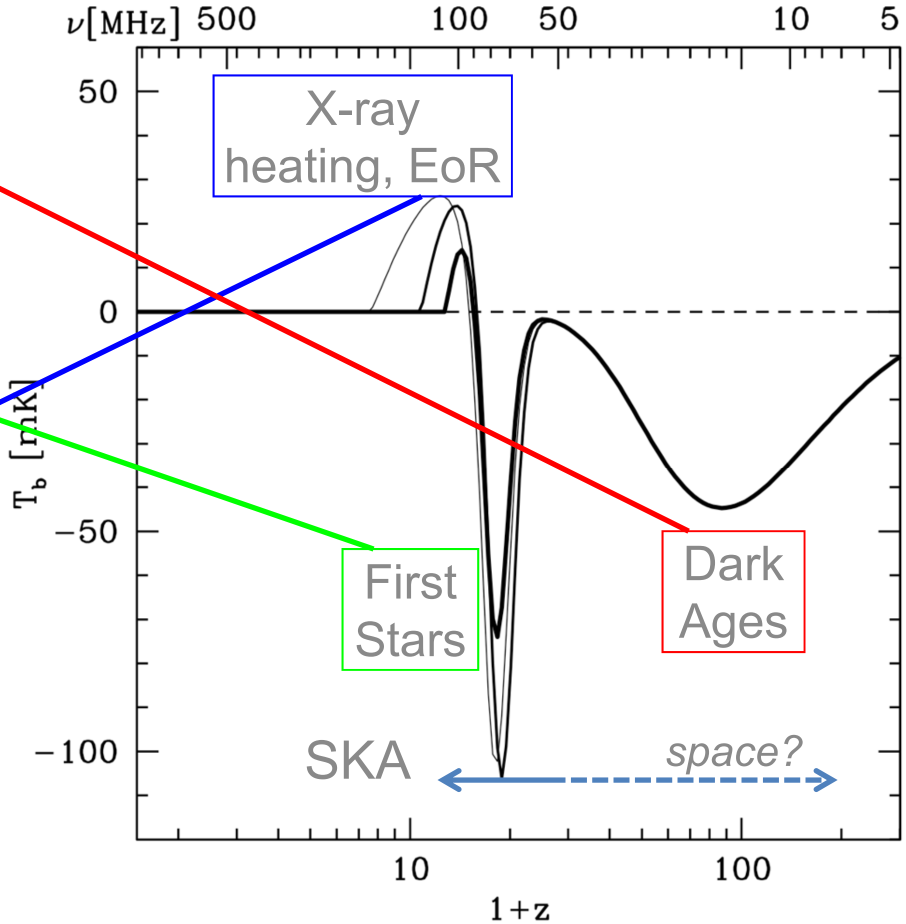
  Nuclear equation of state

Galaxies Across Cosmic Time, The Galactic Neighborhood, Stellar and Planetary Formation

- Galaxies and the Universe
  - How did the Universe emerge from its Dark Ages?
  - How did the structure of the cosmic web evolve?
  - Where are most of the metals throughout cosmic time?
  - How were galaxies assembled?
- Stars, Planets, and Life
  - How do planetary systems form and evolve?
  - What is the life-cycle of the interstellar medium and stars? (biomolecules)
  - Is there evidence for life on exoplanets? (SETI)

Evolution of the Universe

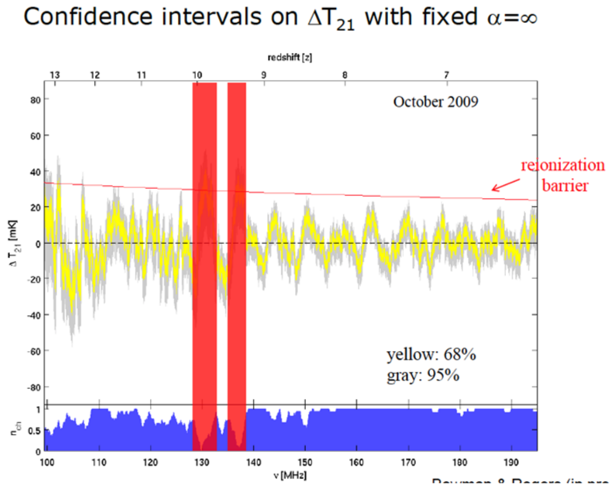




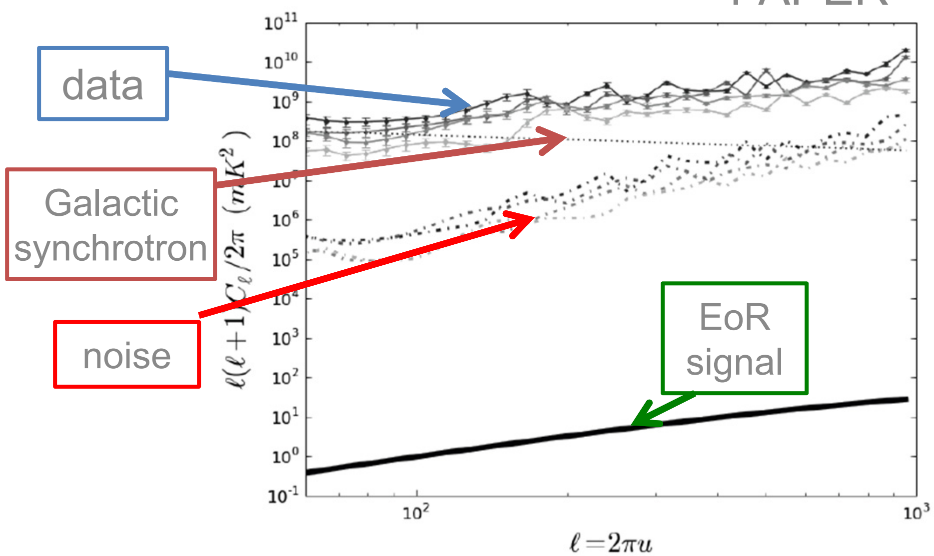
(Pritchard & Loeb 2008)

Evolution of the Universe
Epoch of Reionization

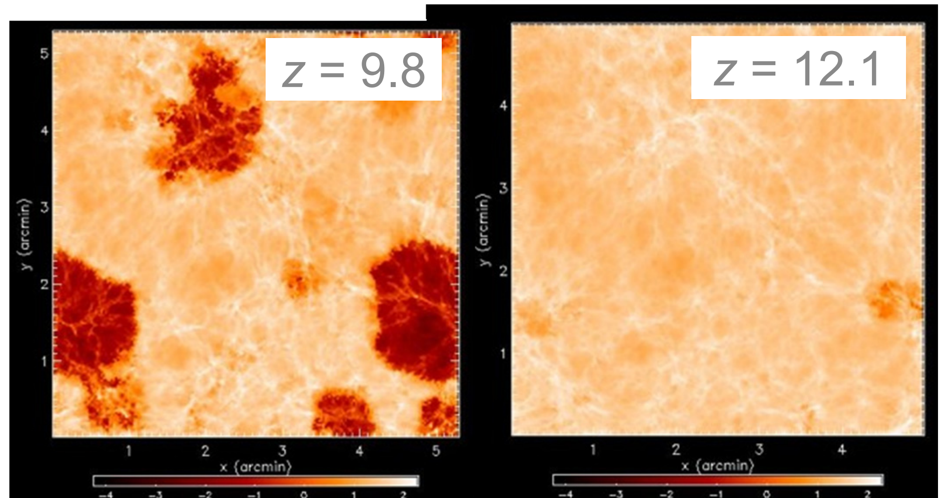
EDGES
(Bowman et al. 2008)



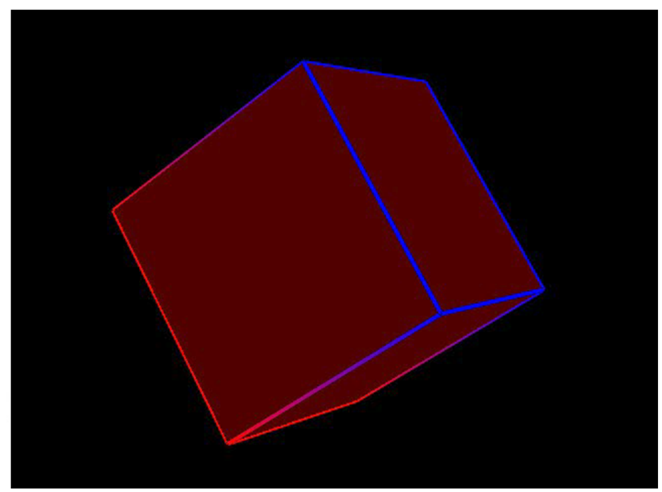
PAPER



Parsons et al. 2009; arXiv:0904.2334



SKA objective: Image the IGM transition in the H I (21-cm) line

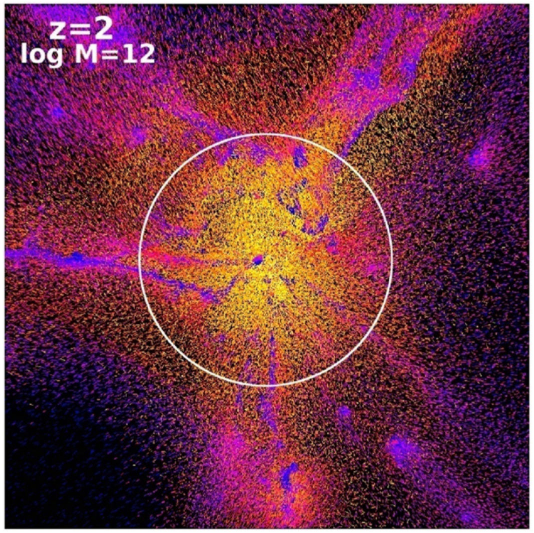


Furlanetto et al.; Gnedin

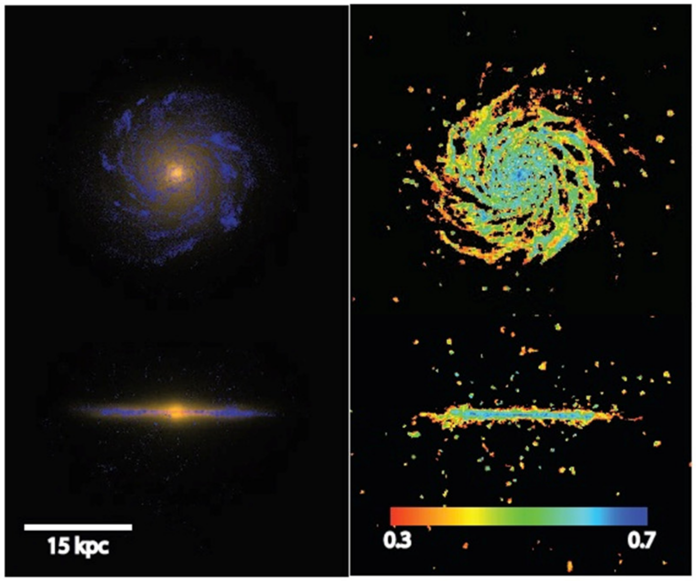
Galaxy Assembly
Stars *and* Gas

- Gas content and dynamics becoming critical part of simulations.
- Astronomy is an *observational* science.
- ➢ Need observations of gas content —over cosmic time—to understand galaxy formation!

observation vs. simulation



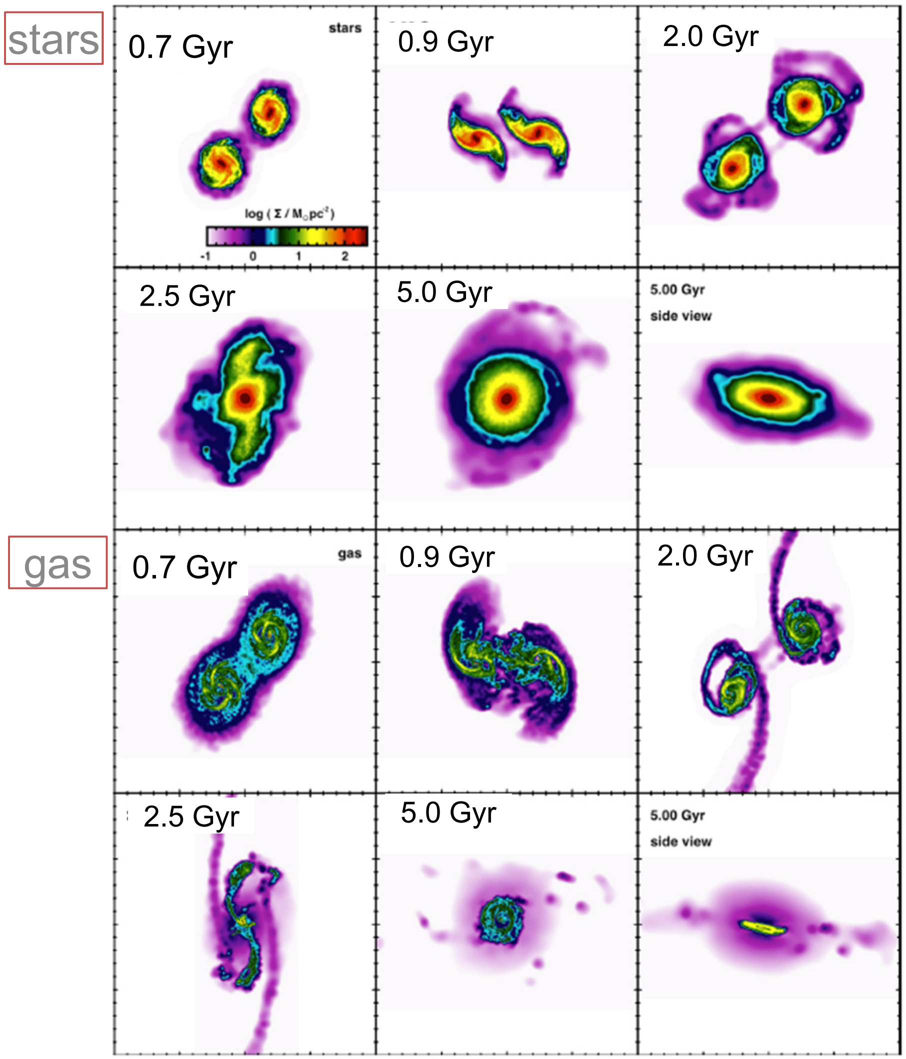
Keres et al.



Eris simulation (Guedes et al.)

NGC 6946 (T. Oosterloo)

Galaxy Assembly
The Role of Mergers



(Moster et al. arXiv:1104.0246)

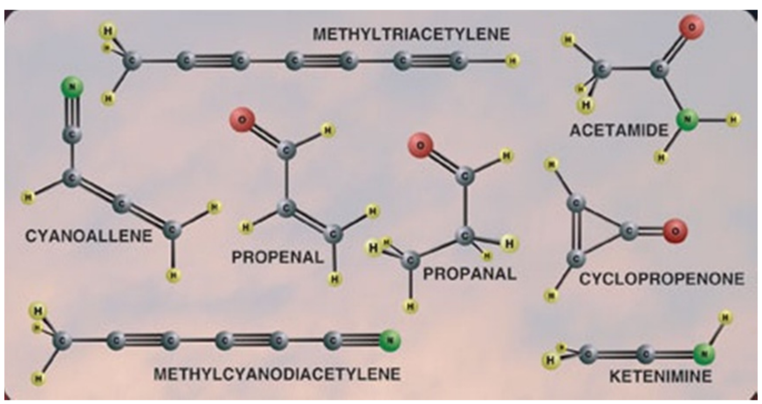
- Mergers are recognized as important aspect of galaxy evolution and formation
- Gas can be sensitive tracer of interactions, long after original event took place

  E.g., Holwerda et al. with THINGS

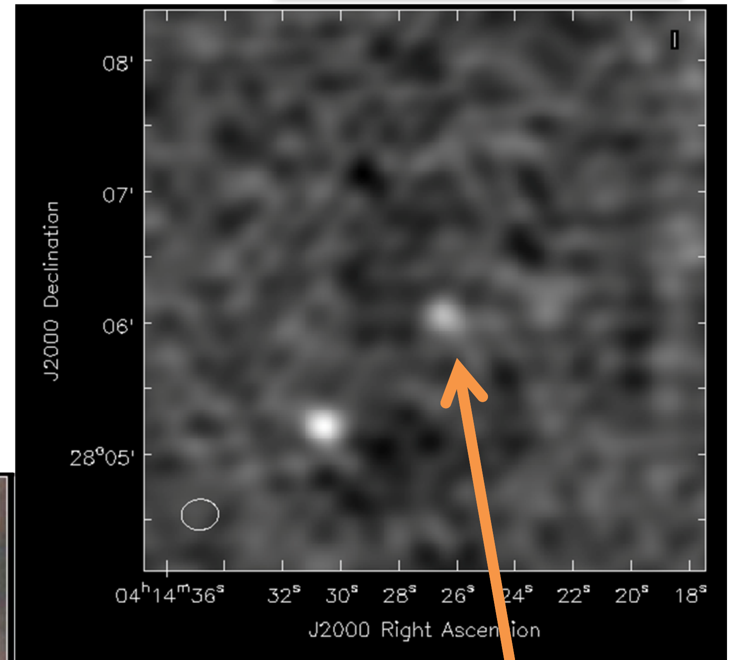
Astrobiology at Long Wavelengths

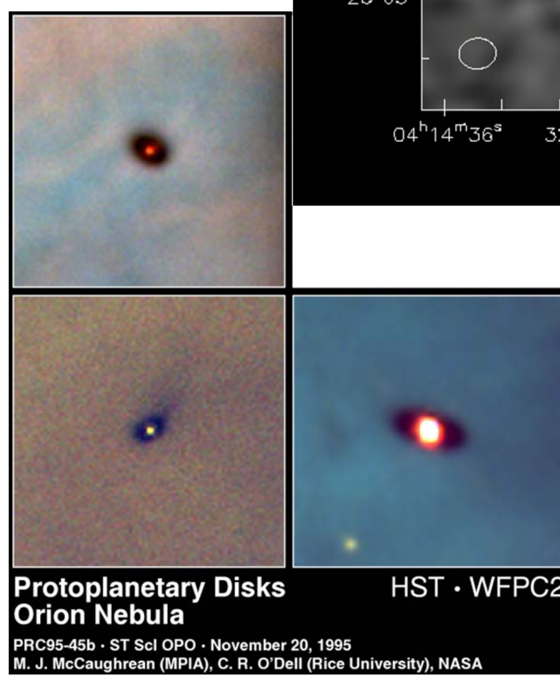
λ > 1 cm

- Not affected by dust
- Complex molecules have transitions at longer wavelengths
- “Waterhole” (1.4–1.7 GHz)
- Magnetically-generated emissions from extrasolar planets

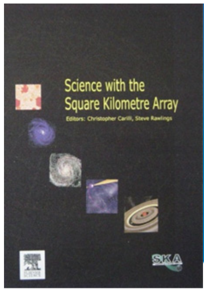


Complex organic molecules detected at radio wavelengths





EVLA 6 cm observations of protoplanetary disks; PEBBLES on e-MERLIN coming soon



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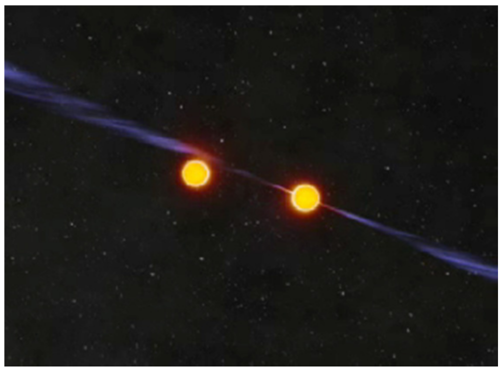
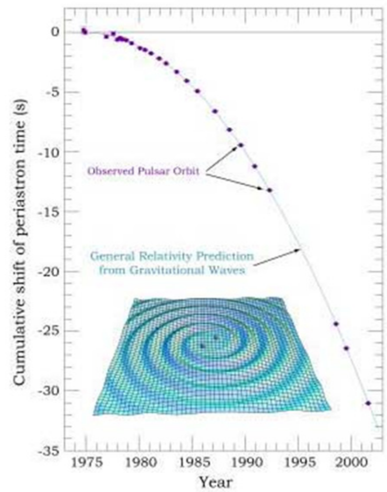
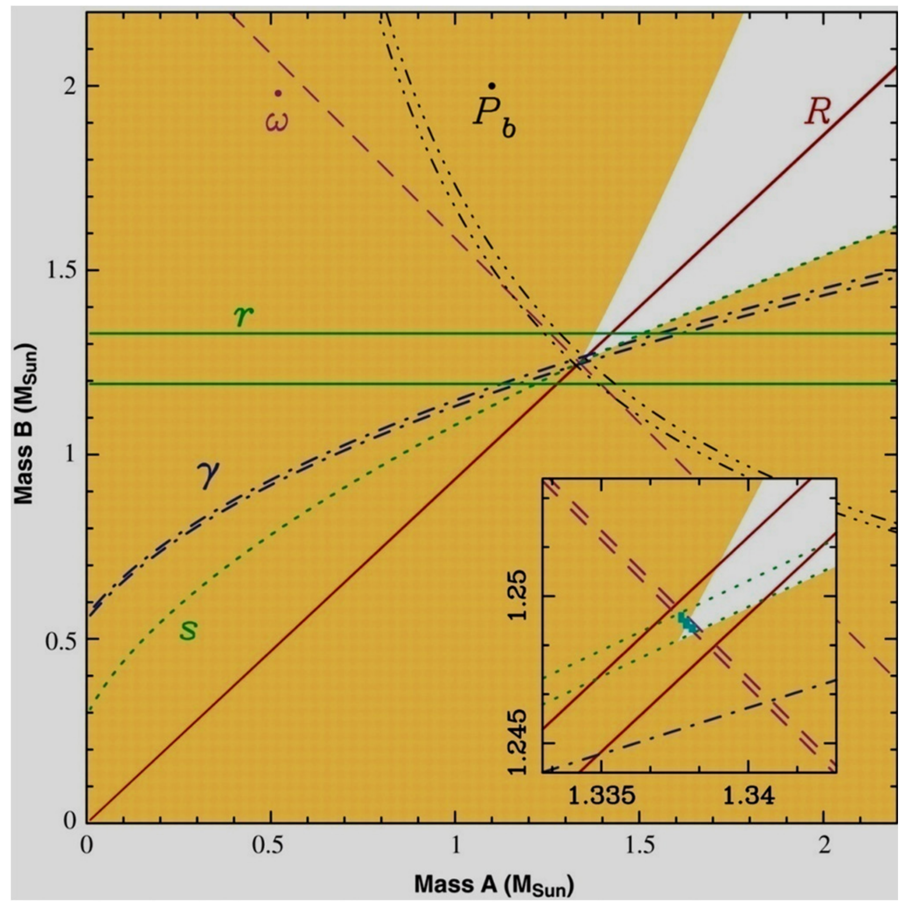
Did Einstein Have the Last Word on Gravity?

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}/c^4$$





PSR J0737–3039



Kramer et al.

Relativistic binaries probe

1. Equivalence principle
2. Strong-field tests of gravity

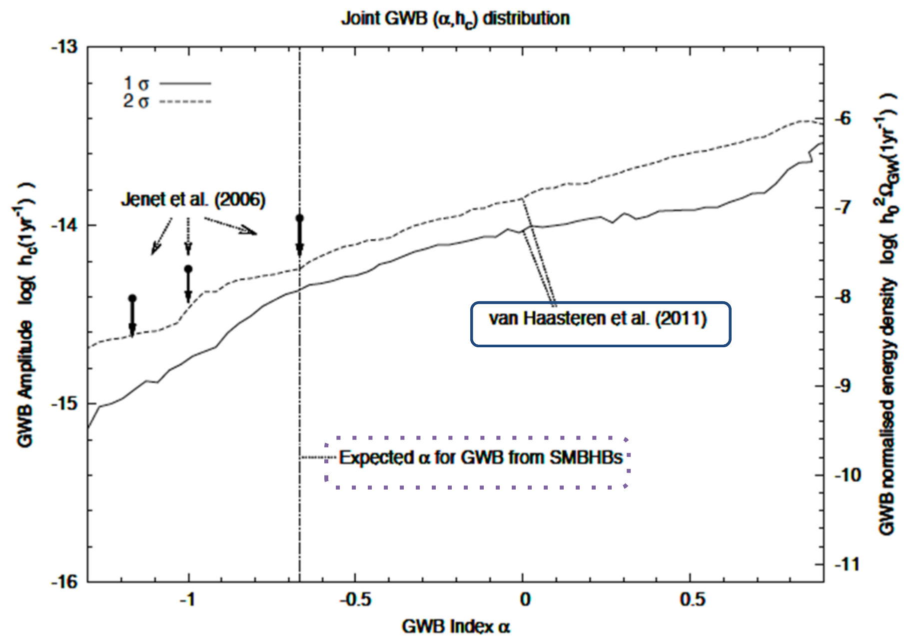
- Neutron star-neutron star and neutron star-white dwarf binaries known

? Black hole-neutron star binaries?

SKA: Gravitational Wave Detector

Test masses on lever arm

- Pulsar Timing Array = freely-falling **millisecond** pulsars
- LIGO = suspended mirrors
- LISA = freely-falling masses in spacecraft

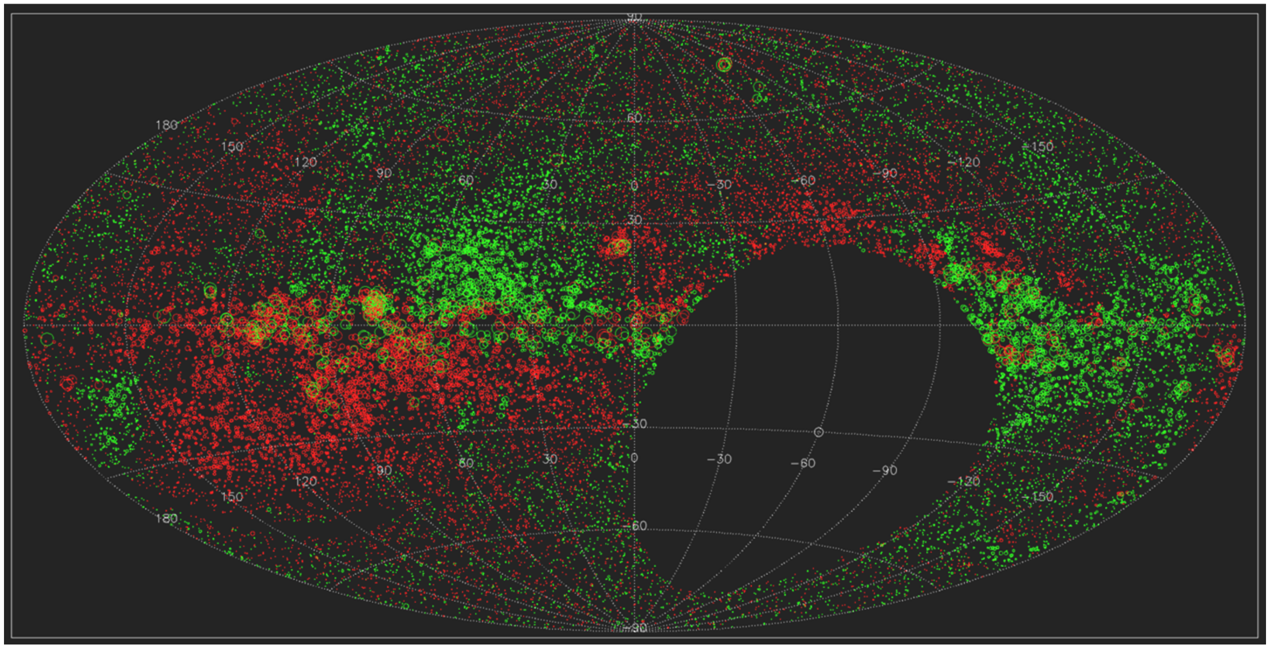


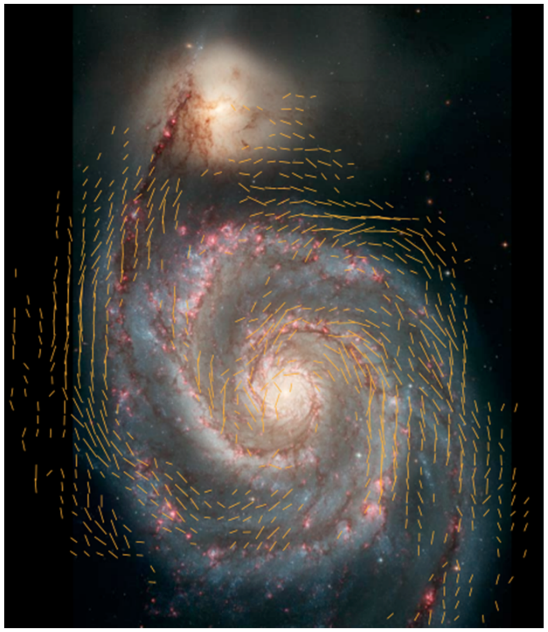
Pulsar timing arrays starting to provide results from ensemble of pulsars

- EPTA (van Haastern et al., *above*)
- PPTA (Yardley et al.)
- *NANOGrav (Demorest et al.)*

Origin & Evolution of Cosmic Magnetic

- Magnetic fields are fundamental, but poorly constrained
  - Affects galaxy, cluster evolution?
  - Affects propagation of cosmic rays in ISM and IGM
- All-sky rotation measure surveys provide **B** fields along lines of sight
- Continuum in I, Q, and U!





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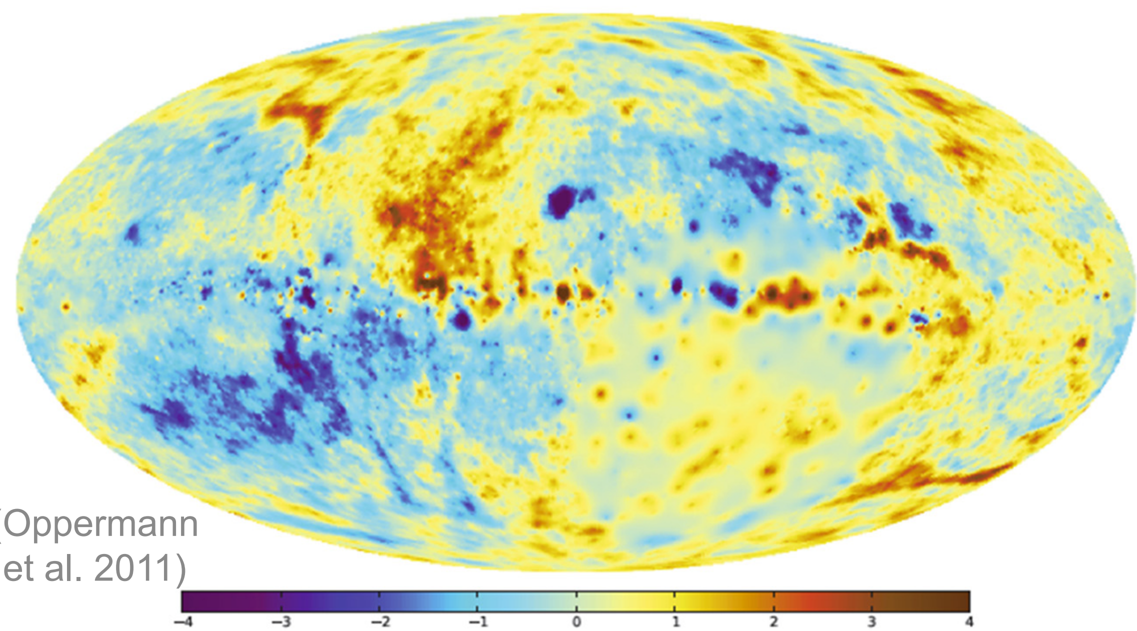
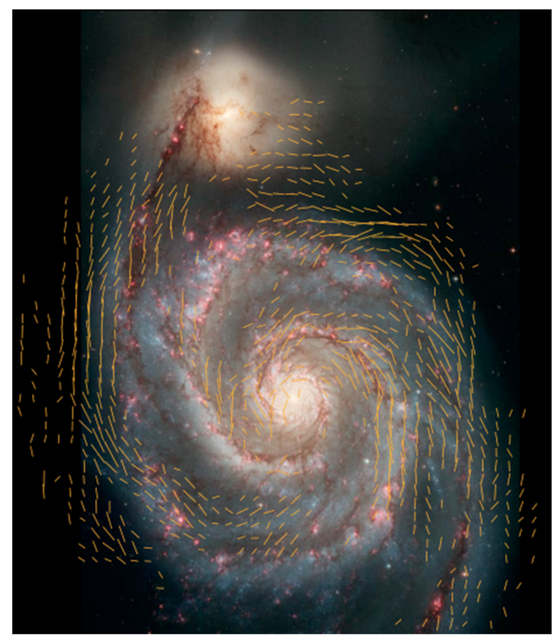
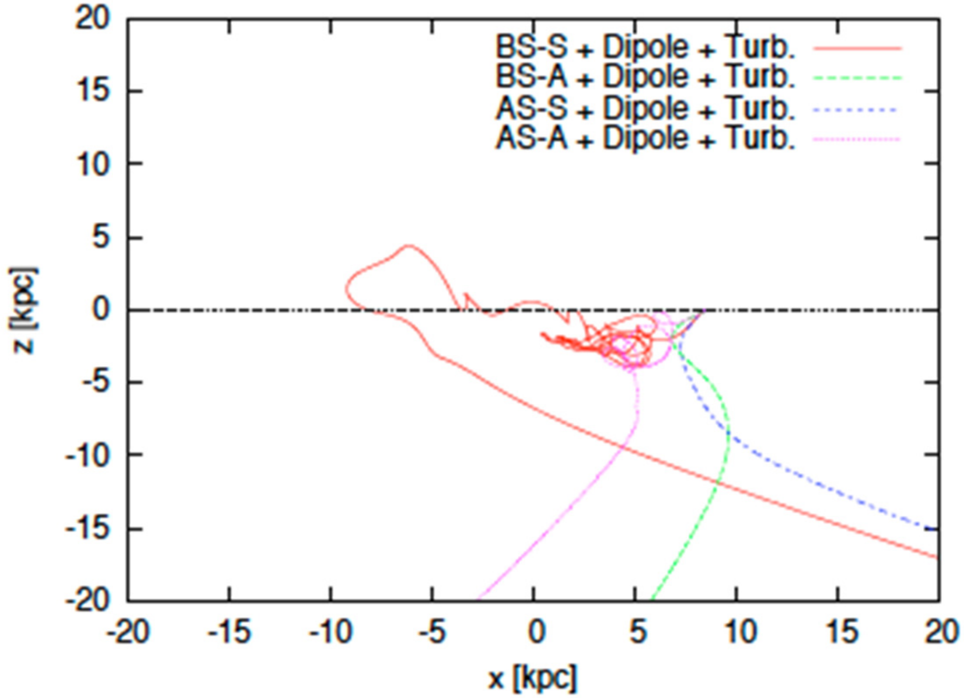


(Oppermann et al. 2011)



Magnetic Fields and Cosmic Rays

- Are ultra-high energy cosmic rays (UHECRs) produced in nearby AGN?
- Galactic magnetic field influences cosmic ray propagation
- ➢ Different models of Galactic field imply different arrival directions
  - – Axi-symmetric vs. bi-symmetric?
  - – Field directions above and below the Galactic plane
  - – Effect of turbulence?
  - – …?



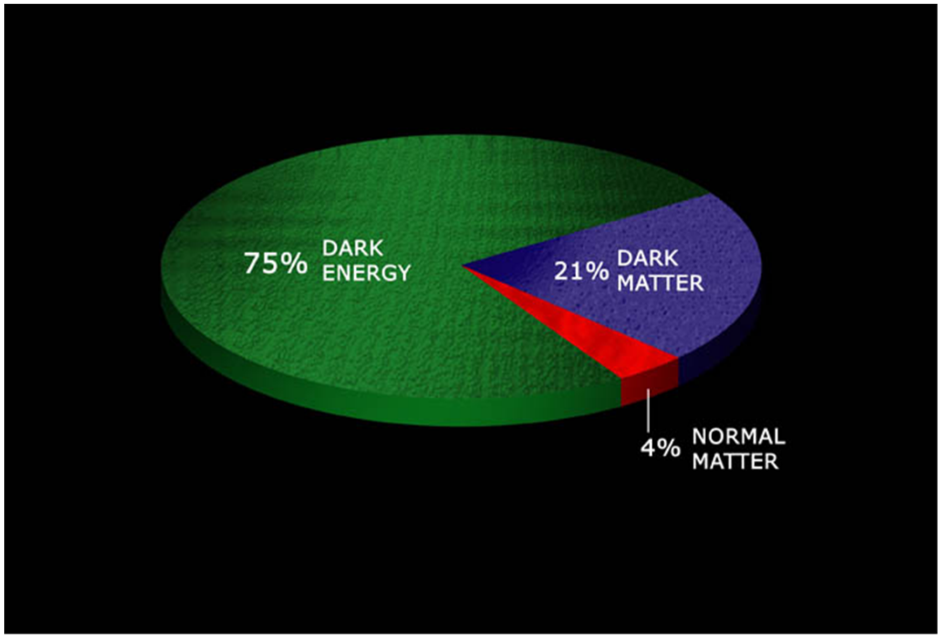
Takami, arXiv:1104.0278

Cosmology and Gravity

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}/c^4$$

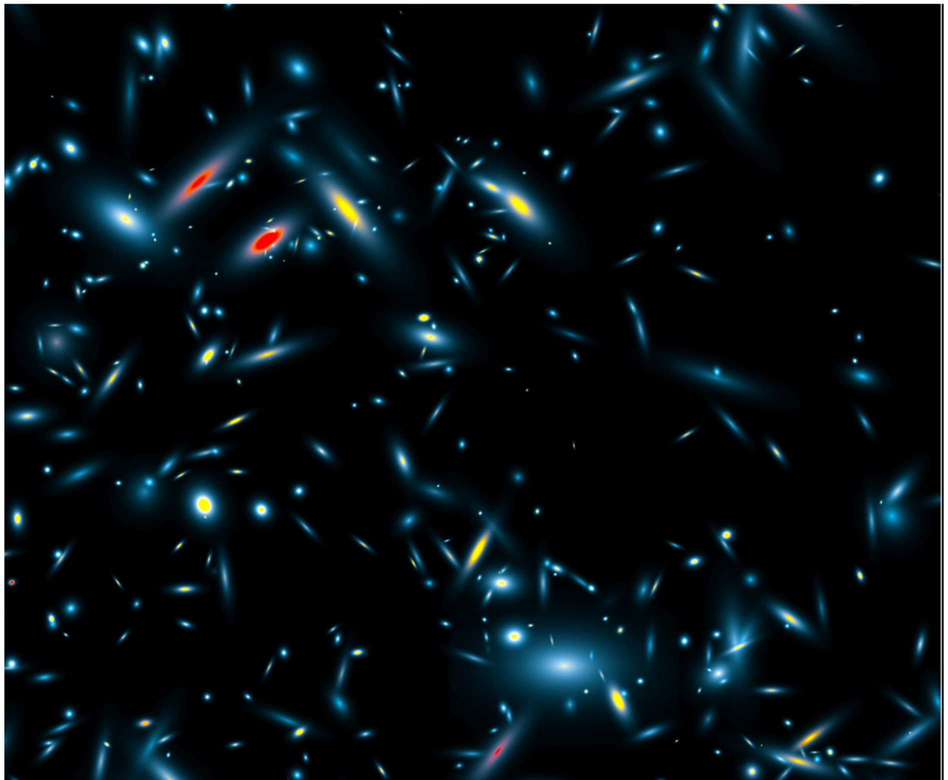
Origin and Fate of the Universe

- Era of "precision cosmology"
  … or precision ignorance
- Need to sample a substantial volume of the Universe
- Volume ~ $D^2 \, \Delta D \, \Omega$
  - D – distance; Ω – solid angle
  - Surveying to larger D is difficult ➔ need larger telescopes
    "square kilometre" of SKA
  - Surveying larger sky areas Ω "just" requires more observing time

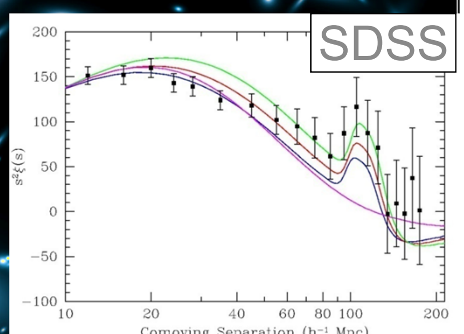


Composition of the Universe

Cosmology and Sky Surveys



SKADS Simulated Sky



- Image the sky, locating galaxies

  Analysis of locations compared with cosmological models to constrain parameters

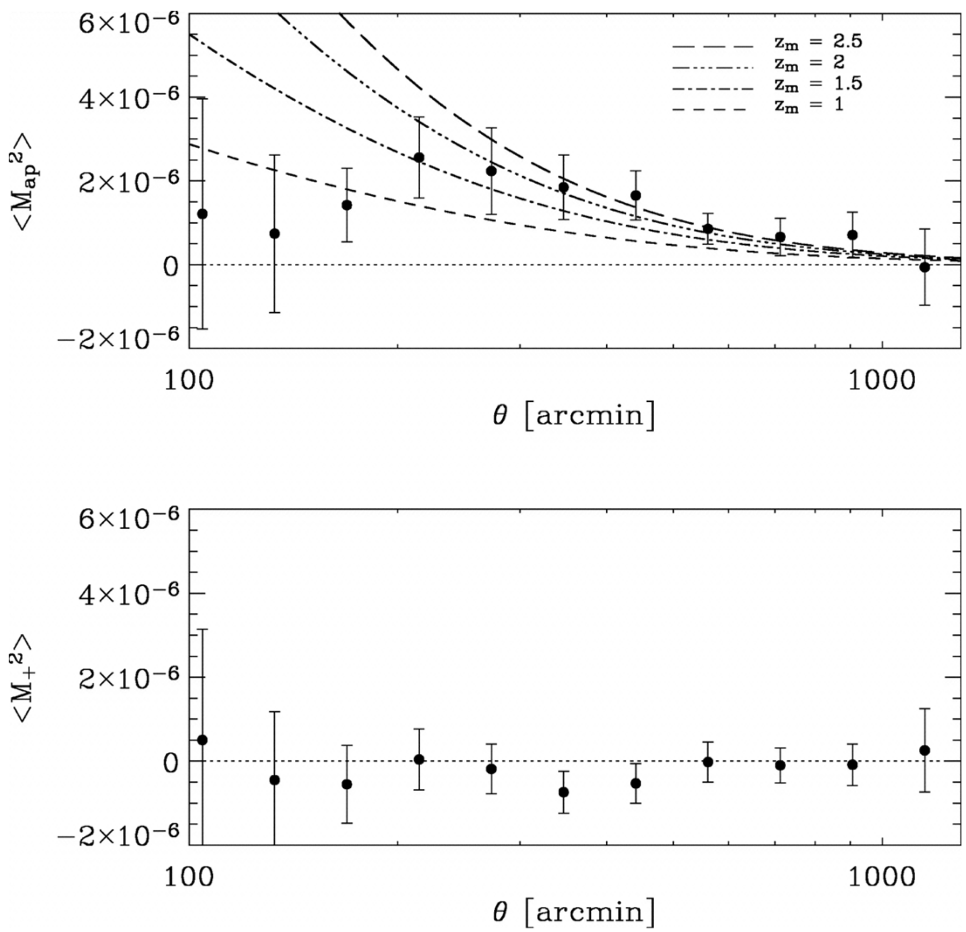
- Two broad classes of surveys
  - Continuum: e.g., NVSS, FIRST, *ASKAP/EMU, WSRT/APERTIF/WODAN*
  - Spectroscopic: SDSS, Arecibo ALFALFA, *ASKAP/WALLABY, SKA H I survey*

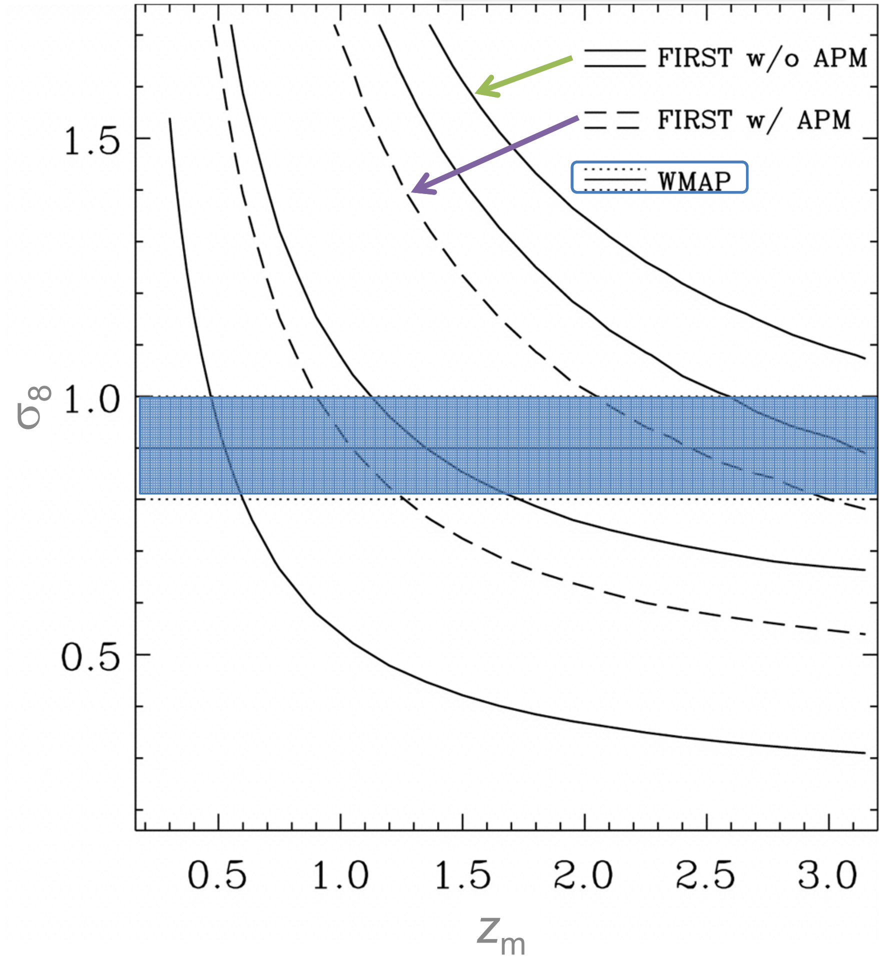
    Spectroscopic surveys locate in **3-D space!** very powerful

- Ultimate goal: spectroscopic survey of 1 billion galaxies

Cosmology and Gravity

Detection of weak lensing (E modes) from FIRST (Chang et al.)





Radio observations should have fewer (different) systematics

21st Century Astrophysics

Fundamental Forces and Particles

- Gravity
- Magnetism
- Strong force

Origins

- Galaxies and the Universe
- Stars, Planets, and Life

"The Universe is patiently waiting for our wits to grow sharper."

Photon frequency /wavelength / energy

Time

Polarization

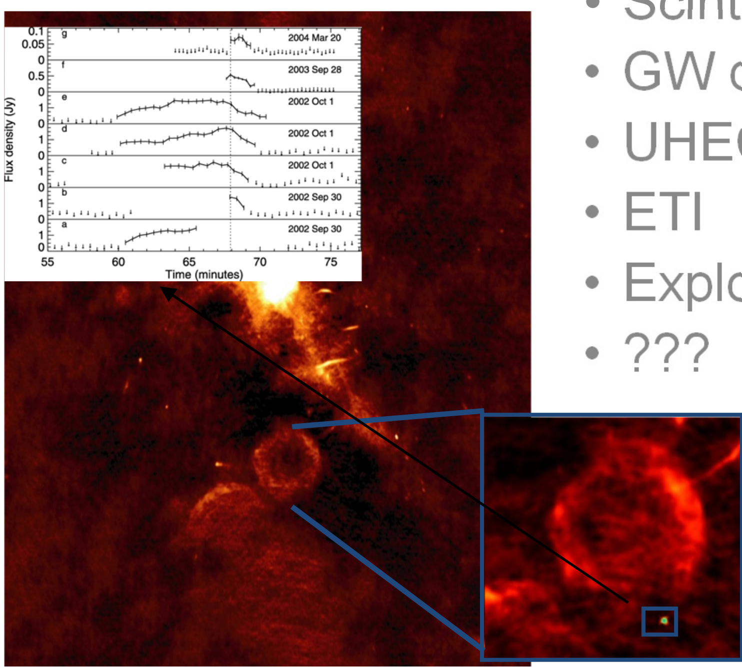
Sensitivity

Field of View

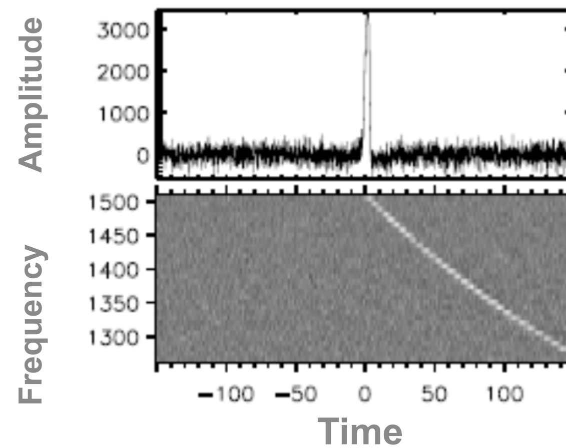
Angular Resolution

The Dynamic Radio Sky

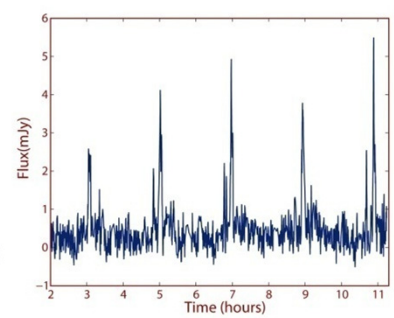
- Neutron stars
  - Magnetars
  - Giant pulses
  - Short GRBs?
- Microquasars
- Tidal Disruption Events

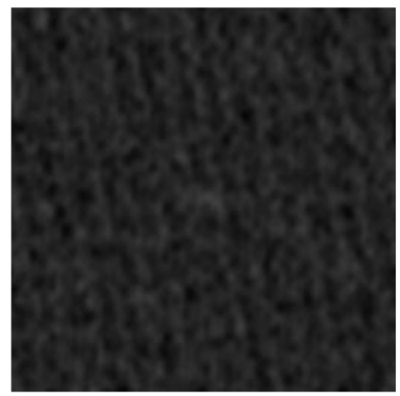


- GRBs (γ-ray loud; γ-ray quiet?)
  - Afterglows
  - Prompt emission?
- Sub-stellar objects
  - Brown dwarfs
  - Extrasolar planets?
- Scintillation
- GW counterparts
- UHECRs
- ETI
- Exploding black holes
- ???

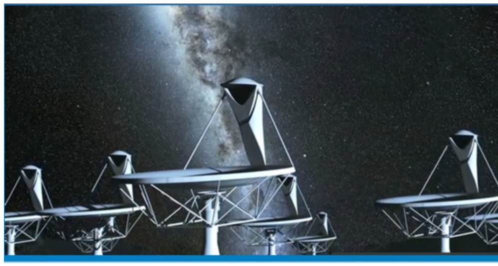


Rotating Radio Transients (RRATS)



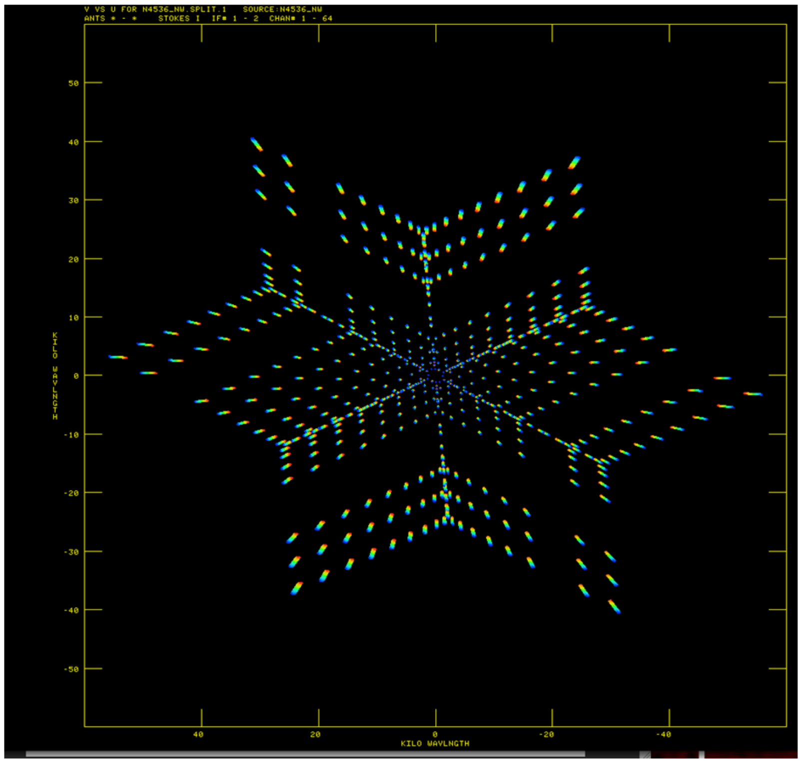


Pulsating Brown Dwarfs



Imaging with Arrays

Fourier transform (*u*-*v*) plane

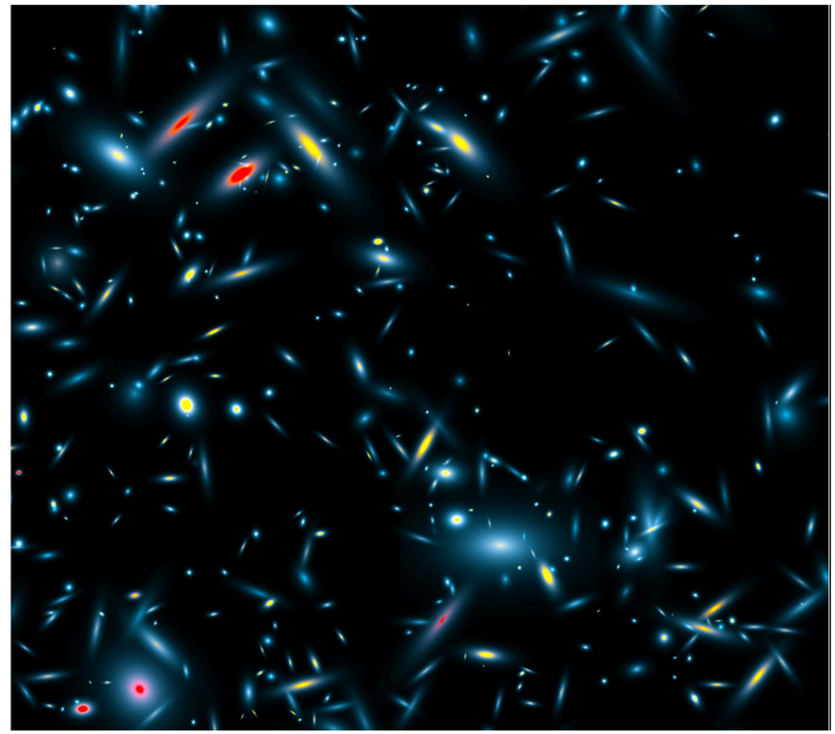


$N_{data} \sim N_{antenna}^2 \, N_{frequency} N_{time}$

Fourier Transform

↔

Image plane



Exploring the Universe with the world's largest radio telescope

Imaging Surveys

Requirements

- Many antennas in order to provide sensitivity and image quality
  large $N_{antenna}$
- Spectral resolution because of wide-field effects, line emission from galaxies, or both
  large $N_{frequency}$
- Long integrations in order to obtain adequate signal-to-noise ratio
  large N_{time}, e.g., 1 hr at 1 s sampling?

$$N_{data} \sim N_{antenna}^{2} N_{frequency} N_{beams} N_{time}$$

ASKAP	SKA Phase 1	SKA Phase 2
$N_{antenna} = 30$	$N_{anntena} \sim 250$	$N_{antenna} \sim 1000$
$N_{beams} = 30$	$N_{beams} = 1$	$N_{beams} = 1?$
$N_{frequency} \sim 16k$	$N_{frequency} \sim 16k?$	$N_{frequency} \sim 16k?$

Imaging Surveys II

ASKAP	SKA Phase 1	SKA Phase 2
$N_{antenna} = 30$	$N_{anntenna} \sim 250$	$N_{antenna} \sim 1000$
$N_{beams} = 30$	$N_{beams} = 1$	$N_{beams} = 1?$
$N_{frequency} \sim 16k$	$N_{frequency} \sim 16k?$	$N_{frequency} \sim 16k?$
$N_{time} \sim 4k$		
$N_{data} \sim 1.8 \times 10^{12}$	$N_{data} \sim 4 \times 10^{12}$	$N_{data} \sim 65 \times 10^{12}$
$\mathbf{N_{OPS} \sim 18 \times 10^{15}}$	$\mathbf{N_{OPS} \sim 40 \times 10^{15}}$	$\mathbf{N_{OPS} \sim 650 \times 10^{15}}$

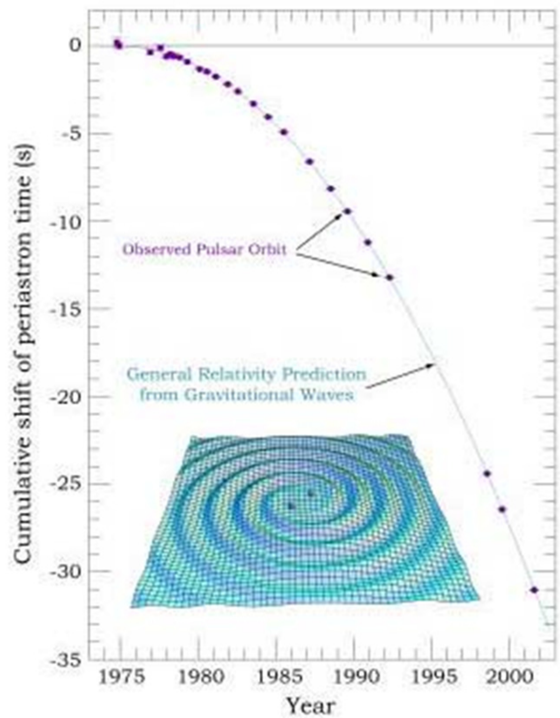
- Imaging is more than "just" an FFT.
  Gridding, deconvolution, wide-field corrections, self-calibration, …
- Community estimates are 10^4 to 10^5 ops per visibility datum(!).
- Leads to significant power challenges
  - Related to moving data on/off chips
  - Careful design can yield significant savings, e.g., D'Addario (SKA Memo 130)

Fundamental Physics with Radio Pulsars

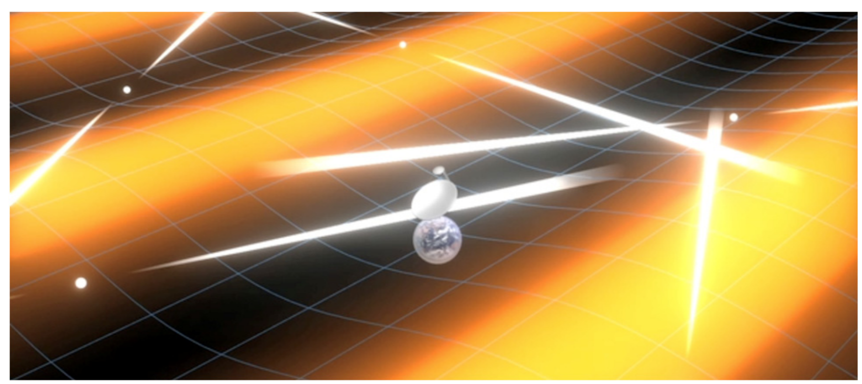
Arrival times of pulses from radio pulsars can be measured with phenomenal accuracy

- Better than 100 ns precision in best cases
- Enables high precision tests of fundamental physics
  - Theories of gravity, gravitational waves, nuclear equation of state
  - 1993 Nobel Prize in Physics
- Problem: Not all pulsars are equal!
- Good “timers” < 10% of total population
- Need to find many more!

➢ All-sky survey



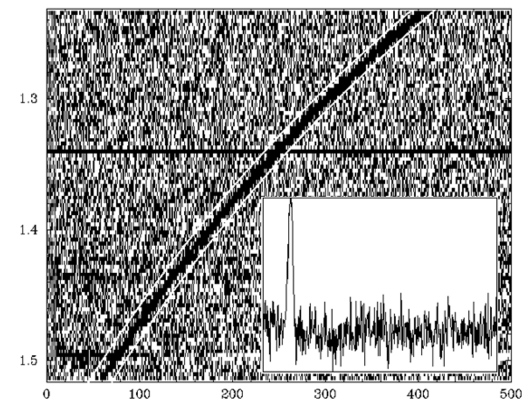
Ultra-relativistic binaries & gravitational wave studies



Pulsar Surveys I

Requirements

- Large bandwidths because pulsars are faint
- Long integration times because pulsars are faint
- Rapid time sampling in order to resolve pulse profile
- Narrow frequency channelization in order to mitigate interstellar scattering



- For a "pixel" on the sky, accumulate data for a time Δt over a bandwidth $\Delta \nu$

    Suppose Δt = 20 min., $\Delta \nu$ = 800 MHz

- Time sampling δt with frequency channelization $\delta \nu$

    For GBT GUPPI, δt = 81.92 μs, $\delta \nu$ = 24 kHz

➢ 60 GB data sets per pixel …

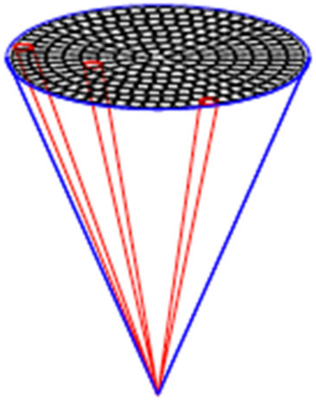
Pulsar Surveys II

For GBT

- At 800 MHz, “pixel” ~ 16' = 0.3°
- About 350 kpixels in the sky
- 20 PB data set

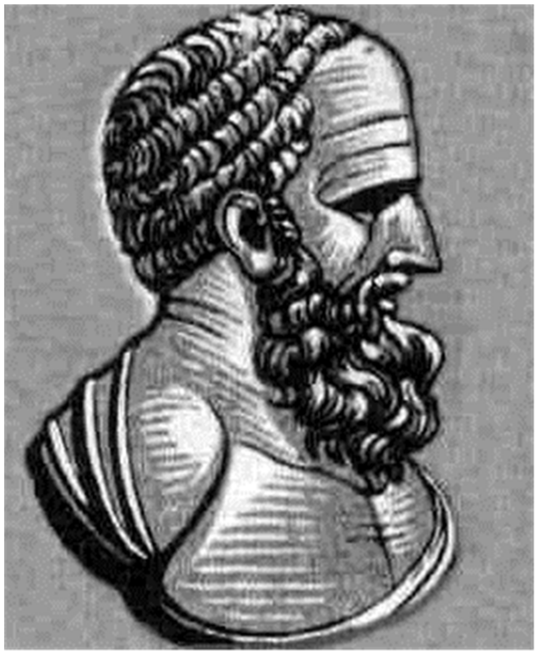
For SKA

- At 800 MHz, “pixel” = 1.2'
- About 76 Mpixels in the sky
- 4.6 EB data set



Data Intensive Astronomy
("There is nothing new under the Sun.")

Data Volumes



Ιππαρχοʃ (Hipparcus)
- ca. 135 BCE
- Stellar catalog with 850 entries

➢ **SKA pulsar survey**

Computational Limitations

Harvard computers
- Production of stellar plates and spectra ("data rate") was increasing enormously
- Examined and classified telescope output

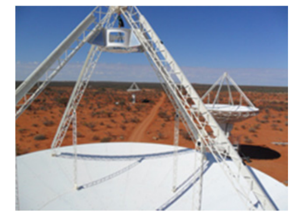
➢ **SKA all-sky survey**

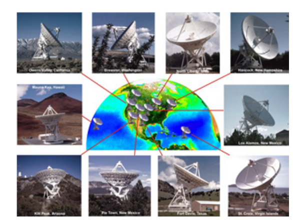
SKA Pathfinding

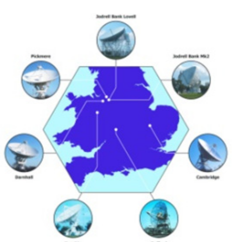
- SKA is ultimate goal, though long-term program
- Precursors and many pathfinders in existence or under construction

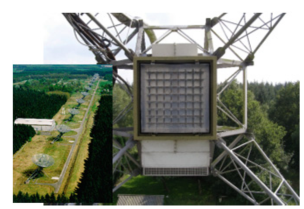
➢ Learn lessons from the Precursors and pathfinders across the full range of experience

Hardware, (firmware), software, data processing, operational modes, …







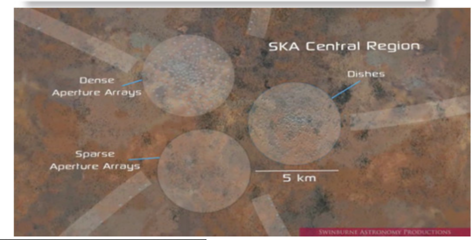


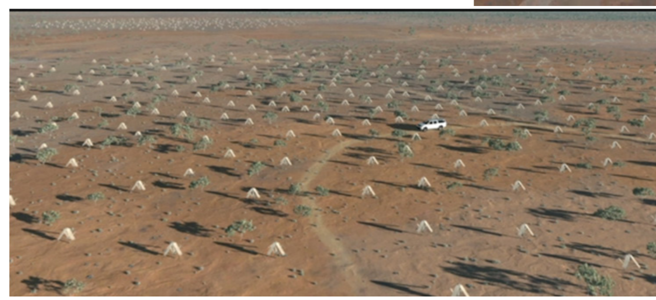
Square Kilometre Array

The Global Radio Wavelength Observatory

- Originally: “Hydrogen telescope”

  Detect H I 21-cm emission from Milky Way-like galaxy at $z \sim 1$





- SKA science much broader

  ⇒ Multi-wavelength, multi-messenger

- On-going technical development
- International involvement